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FOR

IMAGE SEGMENTATION USING BRANCH AND BOUND ANALYSIS

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IMAGE SEGMENTATION USING BRAND AND BOUND ANALYSIS

FIELD

[0001] An embodiment of the invention relates to imaging in general, and more specifically to image segmentation using branch and bound analysis.

BACKGROUND

[0002] In modern technology, particularly in electronics, devices are moving to smaller and smaller structures, which may be referred to as nano-structures. It is expected that further reductions in scale will continue to be developed in the future. For example, microelectronic devices have been greatly reduced in size, thereby reducing the size of structures such as the wire connections in microelectronic devices.

[0003] The reduction in device size has created new challenges for imaging of devices. Imaging of structures may be required for many purposes, including analysis and debugging of manufactured devices. As the devices are reduced in size, structures within the devices may become small enough that conventional imaging techniques are insufficient, thereby complicating the process of device analysis.

[0004] In particular, noise becomes a significant factor in the imaging of small structures. The noise levels that are present in images of extremely small structures may be very high. Noise levels are a problem that will intensify as the structures are subject to further miniaturization.

[0005] As a result of high noise levels, difficulties may arise in correctly interpreting what can be seen in images of nano-structures. In particular, the analysis and debugging of microelectronic devices becomes more challenging as the noise in the

images overwhelms the structures in images, making it increasingly difficult to discern what is and is not shown in an image.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] The invention may be best understood by referring to the following description and accompanying drawings that are used to illustrate embodiments of the invention. In the drawings:

[0007] **Figure 1** illustrates an embodiment of a structure subject to imaging;

[0008] **Figure 2** illustrates embodiments of models that may be used in imaging;

[0009] **Figure 3** illustrates an embodiment of an image with possible segmentations;

[0010] **Figure 4** is a flow chart illustrated an embodiment of image segmentation;

[0011] **Figure 5** illustrates an embodiment of an imaging environment; and

[0012] **Figure 6** is an illustration of a computer that may be used in image processing according to an embodiment of the invention.

DETAILED DESCRIPTION

[0013] A method and apparatus are described for image segmentation using brand and bound analysis.

[0014] Before describing an exemplary environment in which various embodiments of the present invention may be implemented, some terms that will be used throughout this application will briefly be defined:

[0015] As used herein, "nano-structure" means a small structure of any kind. The term includes, for example, a microelectronic structure.

[0016] As used herein "segmentation" means separation of an image into segments.

[0017] According to an embodiment of the invention, a large number of possible segmentations of an image are considered using an objective function to determine which segmentation maximizes a criterion. The set of possible segmentations and the objective function are specified to meet the conditions of the particular situation.

[0018] Under an embodiment of the invention, an algorithm is utilized to explore a space of segmentations of an image using a branch-and-bound technique. The algorithm eliminates the portions of the segmentation space that are proved to be poor candidates and explores in further detail the more promising portions of the segmentation space.

[0019] Under an embodiment of the invention, an image is segmented using a model of the observed structure. In the embodiment, the shape properties of the segmentations are defined and, among all segmentations with such shape properties, the segmentation that maximizes an explicit homogeneity criterion is obtained. For example,

in an image that provides a lighter colored structure against a darker background, the segmentation that maximizes homogeneity for dark and light regions of the device in relation to the geometric model of the structure is obtained.

[0020] In one simple example, a straight-line segmentation of an image into two regions may be utilized to minimize the intensity variation within the regions. In this example, any segmentation divides the image into a first region and a second region. The segmentation that will best fit the image will fit the model and contain a minimal intensity variation in the first region and the second region.

[0021] In one example, an image may be taken of a wire or other metal portion on a background, such as a silicon wafer substrate. The wire generally will generate more intense reflection than the silicon. However, in microelectronics, the structures will be extremely small and a large amount of noise may exist in the image. For this reason, it may be difficult to correctly interpret what is contained in the image. Under an embodiment of the function, certain expected wire geometries may be used to form models, and segmentations of the image may be based upon these models. Under an embodiment of the invention, a function will provide a higher priority to segmentations that result in an area of high intensity pixels in a background of low intensity pixels, which would represent a wire set against the silicon. The set of possible segmentations reflects what is known about the geometry of the wire, thus what is included in the model for the wire.

[0022] **Figure 1** illustrates an embodiment of a structure subject to imaging. Figure 1 contains a simplified model for purposes of explanation. Figure 1 shows a particular wire structure **110** that is present in a microelectronic device and an image of

this device with noise **120**. In this illustration, the structure is intended to represent a wire with a T-junction, with the lighter colored wire being presented on a darker silicon background. In actual images, the noise level for the image may be high and the structure may be much more difficult to discern. Under an embodiment of the invention, the image **120** is segmented according to models of structures. In this example, the structure is segmented according to geometric models of wiring structures that are expected to found in the image.

[0023] **Figure 2** illustrates embodiments of models that may be used in imaging. In this particular example, the models are geometric models that represent wires on a silicon background, but embodiments of the invention are not limited to any particular type of structure or model. In Figure 2, the models shown are of a wire **210**, a wire with a T-junction **220**, a wire corner **230**, and a wire tip **240**. These models presented here are only certain examples of models that may be used in a wiring environment. Each model may be rotated or reflected to form other variations. Each geometric model then may be used to produce many segmentations of an image.

[0024] **Figure 3** illustrates an embodiment of an image with possible segmentations. In this illustration, the image is of a T-junction **310**, which is a possible wire structure that may be found in a microelectronic device. The segmentations in this illustration are based on a geometric model of a T-junction. The illustrated segmentations differ based on how the segmentations will allocate certain pixels, such pixels being in the indicated cross-hatched area **320**. In this illustration, the segmentations vary according to four parameters, although the number of parameters will vary depending on the circumstances. In this illustration, the parameters are the position

of the top horizontal line **330**, the position of the bottom horizontal line **340**, the position of the left vertical line **350**, and the position of the right vertical line **360**. However, the segmentations agree on many of the pixels. For the segmentations that are shown in Figure 3, these pixels are the pixels that are outside of area **320**. It is possible to determine, based on the pixels on which the segmentations agree, that all of the segmentations in the range being considered will generate no more than a certain maximum contrast.

[0025] Under an embodiment of the invention, in order to consider a large set of segmentations (which, in theory, can approach infinity) in a reasonable amount of time, bounds are implemented. Each segmentation has a certain quality relating to the image. For example, the quality of a given segmentation may represent the homogeneity of dark and light regions of the image as the image is divided by the segmentation. For any set of segmentations, the bound associated with the set is a number that is guaranteed to be at least as high as the quality of the best segmentation in the set. In one example, for a set of possible segmentations that have some similarities, it is possible to evaluate a bound for the quality of the segmentation in the set. If the bound is low enough, the entire set may be eliminated without looking in detail at the individual segmentations in the set. This is accomplished by finding the pixels on which all of the segmentations in the set agree. The intensity of such pixels (although color or other characteristic may also be used) that are segmented in the same way by all the segmentations being considered can be used to calculate the range of possible contrasts between pixels that are inside and outside of the image structure, i.e., the pixels that are inside or outside the wire on a silicon background. Any segmentation in the set would result in a contrast in the range.

Therefore, if the highest possible contrast of the set is low, the entire set of segmentations can be eliminated from consideration.

[0026] Under an embodiment of the invention, a branch and bound algorithm is used to search for an optimal segmentation of an image. The algorithm uses a priority queue to store states, with each state being a set of segmentations. Each state is either a terminal state or a non-terminal state. When a terminal state reaches the head of the queue, the search is terminated. States are designated as terminal according to a certain precision standard. All other states are non-terminal states. When a non-terminal state reaches the head of the queue, the state is removed from the queue, and new states that are subsets of the removed state are then inserted in the queue. The states in the queue are prioritized by the bounds associated with them, and the state with the highest bound is placed at the head of the queue. For example, the priority may represent the contrast between the pixels inside a particular segmentation and the pixels outside the segmentation.

[0027] Under an embodiment of the invention, an image may be viewed as an array P of pixels in two-dimensions:

$$P = \{(i, j) : i = 1, \ldots n_x, j = 1, \ldots n_y\}$$

[0028] Under an embodiment of the invention, each pixel p is associated with a scalar value. For example, $v(p)$ may represent the light intensity of the pixel p. Under another embodiment of the invention, $v(p)$ may represent a vector. For example, $v(p)$ may represent an RGB color vector or a filter response vector.

[0029] Under an embodiment of the invention, l is a segmentation loss function. The segmentation loss function scores each segmentation according to a fixed criterion:

$$l : \boldsymbol{S} \to \mathbf{R}$$

[0030] Under an embodiment of the invention, an algorithm finds a segmentation that maximizes the function l over the set of segmentations $\boldsymbol{S}$. In one possible example, the function l may represent intensity homogeneity, and maximizing l results in maximizing the contrast between pixels inside of a segmentation and pixels outside of the segmentation.

[0031] Under an embodiment of the function, a refining function R breaks up sets of segmentations into smaller sets by mapping a set of segmentations into a collection of sets of segmentations that form a partition of the original set. If a set S is a set of segmentations in the segmentation space $\boldsymbol{S}$, then S is partitioned into sets:

$$S \subseteq \boldsymbol{S}$$

$$R : 2^{S} \to 2^{2^{S}}$$

$$S \to S_1, S_2, \ldots, S_l$$

[0032] Under an embodiment of the invention, a partial segmentation function M will provide the set of all the cells that a pixel may be mapped to by a set of segmentations:

$$M : 2^{S} \times \boldsymbol{P} \to 2^{\{1,\ldots,K\}}$$

[0033] With P being the array or the set of all of the pixels in an image, for any pixel p in a set S of segmentations, the function M may be expressed as:

$$M(S, p)$$

[0034] Under an embodiment of the invention, a partial segmentation loss function exists such that:

$$B : \left(2^{\{1,\ldots,K\}}\right)^{P} \to \mathbf{R}$$

[0035] Under an embodiment of the invention, a function B maps a partial segmentation of the pixels in an image to a value. The value obtained is greater than or equal to all values associated with any segmentation that is consistent with the partial segmentation. In an example of image contrast, this means that the value is greater than or equal to, or thus that the image contrast is greater than or equal to, any segmentation including the partial segmentation.

[0036] Under an embodiment of the invention, states are subsets of a segmentation space S. For any non-terminal state, the states that are immediately reachable from S are given by $R(S)$, which is the refinement of the segmentation set S into smaller segmentation sets. Using the functions provided above and assuming a partial segmentation T is defined by $T(p) = M(S, p)$, representing the cells that p may be mapped to, the priority function L:

$$L : 2^{S} \to \mathbf{R}$$

may be defined as:

$$L(S) = B(T)$$

In this equation, the function L provides a bound for any segment that is an element of the set that is the argument.

[0037] Under an embodiment of the invention, an optimization process for a segmentation of an image may be expressed as follows:

[0038] (1) **Initialization of Process** - The process is begun with an empty priority queue. The state ***S*** for the set of all segmentations is inserted into the priority queue, the state ***S*** having a priority of $L(\boldsymbol{S})$.

[0039] (2) **Extraction from Queue** - The state at the head of the priority queue is extracted, this state initially being the set of all segmentations ***S***. The state is removed from the queue. If the extracted state is a terminal queue, the process is halted and the state is output as the solution to the optimization process. Otherwise, the process continues.

[0040] (3) **Insertion into Queue** - For a set S that has been extracted from the queue, sets of segmentations are produced by the refining function R, $R(S) = \{S_1, S_2, ..., S_k\}$, with the corresponding priorities $L(S_1), L(S_2), ... L(S_k)$. The sets of segmentations that are produced are inserted in the priority queue in the order of the priority of each set.

[0041] (4) **Iteration** - The process returns to (2) Extraction from Queue to address the set of segmentations that is now at the head of the queue.

[0042] Under an embodiment of the invention, the optimization process divides the possible segmentations of an image into sets. The process evaluates upper bounds for each of the sets, this being done with the priority function L. The set with the highest, or most promising, bound goes to the top of the queue, and is then divided into smaller sets and the bounds are then refined. By keeping track of the sets and the associated bounds, it is then possible to identify the best segmentation of the image, and thus the best model for the structure that is present in the image.

[0043] **Figure 4** is a flowchart to illustrate an embodiment of image segmentation. In this illustration, image data is received **405**. For example, the image data may represent the light intensity recorded by each pixel in an array of pixels. The image may be of a structure, such as, for one example, a wire structure of a microelectronic device. An empty priority queue is initialized **410**, and into such queue is inserted the set of all segmentations ***S*** of the image **415**. The segmentations are based on models of the structure, such as geometric models of expected wiring structures for a microelectronic device. The priority queue is arranged in order of priority, thus with the most promising segmentations at the head of the queue.

[0044] The state at the head of the priority queue is extracted **420**. There is a determination whether the state is a terminal state **425**, thus a question whether a particular standard has been reached that would terminate the search for segmentations. If the state is a terminal state, the extracted state is output at the solution to the process, the state representing the resulting segmentation of the image. If the state is not a terminal state, then the state is refined **430**, producing a set of segmentation sets with a greater degree of refinement. The resulting segmentation sets, each having its own priority, are then inserted into the priority queue in order of priority **435**. The process then continues iteratively, returning to the extraction of the state from the head of the queue **420**.

[0045] **Figure 5** illustrates an embodiment of an imaging environment. Figure 5 is a simplified drawing for purposes of explanation and is not intended to include all parts of an imaging system or to illustrate the parts in relative scale. In this example, the subject of imaging is a microelectronic device **510**, which may include a processor or

another electronic device. The microelectronic device **510** includes a number of traces **520**. Under an embodiment of the invention, a focused ion beam (FIB) tool **540** directs a beam of ions **530** on the microelectronic device **510** and receives an image of the device under test with an image receptor **550**. Other embodiments of the invention may be implemented with different types of imaging devices. The focused ion beam tool **540** may produce an image of the microelectronic device **510** for purposes of, for example, analysis and debugging operations. However, the structure of the microelectronic device **510** may be extremely tiny, and, as a result, the level of noise in images may be very high in relation to the actual image. The high level of noise may make it difficult to recognize and evaluate the device under test. Under an embodiment of the invention, the focused ion beam tool **540** may utilize automatic recognition of nano-structures using image segmentation and a branch and bound technique to recognize structures based on certain models of structures in the microelectronic device **510**. Under an embodiment of the invention, data from the focused ion beam tool **540** may directed to a computer or other processing device **560** for processing. Under another embodiment of the invention, the focused ion beam tool **540** may include the processing means in a system. Under an embodiment of the invention, the focused ion beam tool **540** may use the recognition of nano-structures to support automatic operation of the tool, thereby allowing the tool to follow the structure of the wiring of the device under test without requiring a human to interpret the images that are received.

[0046] **Figure 6** is an illustration of a computer that may be used in image processing according to an embodiment of the invention. Under an embodiment of the invention, a computer **600** comprises a bus **605** or other communication means for

communicating information, and a processing means such as one or more processors **610** (shown as **611**, **612**, and continuing through **612**) coupled with the bus **605** for processing information. The information processed may include image data, including images of nano-structures. The image data may be processed to interpret such data.

[0047] The computer **600** further comprises a random access memory (RAM) or other dynamic storage device as a main memory **615** for storing information and instructions to be executed by the processors **610**. Main memory **615** also may be used for storing temporary variables or other intermediate information during execution of instructions by the processors **610**. The computer **600** also may comprise a read only memory (ROM) **620** and/or other static storage device for storing static information and instructions for the processor **610**.

[0048] A data storage device **625** may also be coupled to the bus **605** of the computer **600** for storing information and instructions. The data storage device **625** may include a magnetic disk or optical disc and its corresponding drive, flash memory or other nonvolatile memory, or other memory device. Such elements may be combined together or may be separate components, and utilize parts of other elements of the computer **600**.

[0049] The computer **600** may also be coupled via the bus **605** to a display device **630**, such as a liquid crystal display (LCD) or other display technology, for displaying information to an end user. In some environments, the display device may be a touch-screen that is also utilized as at least a part of an input device. In some environments, display device **630** may be or may include an auditory device, such as a speaker for providing auditory information. An input device **640** may be coupled to the bus **605** for communicating information and/or command selections to the processor **610**.

In various implementations, input device **640** may be a keyboard, a keypad, a touch-screen and stylus, a voice-activated system, or other input device, or combinations of such devices. Another type of user input device that may be included is a cursor control device **645**, such as a mouse, a trackball, or cursor direction keys for communicating direction information and command selections to processor **610** and for controlling cursor movement on display device **630**.

[0050] A communication device **650** may also be coupled to the bus **605**. Depending upon the particular implementation, the communication device **650** may include a transceiver, a wireless modem, a network interface card, or other interface device. The computer **600** may be linked to a network or to other devices using the communication device **650**, which may include links to the Internet, a local area network, or another environment. In an embodiment of the invention, the communication device **650** may provide a link to a service provider over a network. Under an embodiment of the invention, the communications device **650** may be utilized to receive image data for processing.

[0051] In the description above, for the purposes of explanation, numerous specific details are set forth in order to provide a thorough understanding of the present invention. It will be apparent, however, to one skilled in the art that the present invention may be practiced without some of these specific details. In other instances, well-known structures and devices are shown in block diagram form.

[0052] The present invention may include various processes. The processes of the present invention may be performed by hardware components or may be embodied in machine-executable instructions, which may be used to cause a general-purpose or

special-purpose processor or logic circuits programmed with the instructions to perform the processes. Alternatively, the processes may be performed by a combination of hardware and software.

[0053] Portions of the present invention may be provided as a computer program product, which may include a machine-readable medium having stored thereon instructions, which may be used to program a computer (or other electronic devices) to perform a process according to the present invention. The machine-readable medium may include, but is not limited to, floppy diskettes, optical disks, CD-ROMs (compact disk read-only memory), and magneto-optical disks, ROMs (read-only memory), RAMs (random access memory), EPROMs (erasable programmable read-only memory), EEPROMs (electrically-erasable programmable read-only memory), magnet or optical cards, flash memory, or other type of media / machine-readable medium suitable for storing electronic instructions. Moreover, the present invention may also be downloaded as a computer program product, wherein the program may be transferred from a remote computer to a requesting computer by way of data signals embodied in a carrier wave or other propagation medium via a communication link (e.g., a modem or network connection).

[0054] Many of the methods are described in their most basic form, but processes can be added to or deleted from any of the methods and information can be added or subtracted from any of the described messages without departing from the basic scope of the present invention. It will be apparent to those skilled in the art that many further modifications and adaptations can be made. The particular embodiments are not provided to limit the invention but to illustrate it. The scope of the present invention is

not to be determined by the specific examples provided above but only by the claims below.

[0055] It should also be appreciated that reference throughout this specification to "one embodiment" or "an embodiment" means that a particular feature may be included in the practice of the invention. Similarly, it should be appreciated that in the foregoing description of exemplary embodiments of the invention, various features of the invention are sometimes grouped together in a single embodiment, figure, or description thereof for the purpose of streamlining the disclosure and aiding in the understanding of one or more of the various inventive aspects. This method of disclosure, however, is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects lie in less than all features of a single foregoing disclosed embodiment. Thus, the claims are hereby expressly incorporated into this description, with each claim standing on its own as a separate embodiment of this invention.